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Coastal exchange characteristics during unstratified season in southern Lake Michigan

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Introduction

In the Great Lakes, as well as in the coastal oceans, the gradients of many biogeochemically important materials (BIMs) are considerably higher in the offshore direction than in the alongshore direction (BRINK et al. 1992). In the presence of these large gradients, cross-isobath circulation is a primary mechanism for the exchange of material between nearshore and offshore waters. In the coastal regions of the Great Lakes it has been observed that the mean alongshore transport is much larger than the cross-shore transport. However, both the alongshore and cross-shore current components exhibit strong episodic behavior due to wind forcing. In order to understand the cross-shore transport of BIMs, and to quantify the physical processes that are responsible for the nearshore–offshore mass exchange, a multidisciplinary research program, EEGLE (Episodic Events Great Lakes Experiment) was recently initiated by NOAA (National Oceanic and Atmospheric Administration) and NSF (National Science Foundation) in Lake Michigan.

Circulation in the lakes is driven by wind, but the effects of earth's rotation, basin topography, and vertical density structure are also important. During the unstratified season, the higher wind speeds and the absence of the thermocline allow the effects of wind action to penetrate deeper into the water column (BOYCE et al. 1989). In shallow water, the entire water mass moves in the direction of the wind, while return flow occurs in the deeper parts of the lake. This forms two counter-rotating closed gyres (SAYLOR et al. 1980), a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left. These rotary motions or vorticity waves have been suggested as a main mechanism for nearshore–offshore transport in the Great Lakes. SCHWAB et al. (2000) observed the presence of this two-gyre circulation pattern in their numerical experiments during a wind event in March 1998. MCCORMICK et al. (2000) reported time series of currents at a few stations in southern Lake Michigan during this event. In the present study, the focus is on the analysis of time series data at selected stations during the winter of 1999, with particular reference to a northerly wind event in March 1999.

Experimental data

The observation strategy for obtaining the cross-shore and alongshore currents, physical environment, and temperature consisted of three components: (a) moored instruments (b) Lagrangian measurements, and (c) ship-board surveys. In the moored instrumentation time series of currents, winds and temperature data were obtained for the field years of 1997–2000. A maximum of 17 moorings of ADCPs and VACMs were deployed from the 20- to 60-m depth contours by GLERL (Great Lakes Environmental Research Laboratory). As part of the program, Canada Centre for Inland Waters (CCIW) deployed additional instrumentation consisting of seven SACMs and two ADCPs in the shallow waters, at a depth of 12 m, along with two coastal meteorological stations. The complete details of the observational strategy are reported on the EEGLE website (http:\\www.glerl.noaa.gov\eegle\). A subset of current meter data was chosen for further analysis. Among the seven SACMs deployed in shallow water, two of them returned good quality data for the whole winter period from 1 January to 10 April 1999. Four ADCPs at 20, 30 and 40 m have also returned high-quality data during this period (Fig. 1).

Results and discussion

Wind-driven transport is a dominant feature of the circulation in the lakes. The spatial variability of the wind field can have a considerable influence on the circulation pattern in the lake. However, for the time series analysis in this study the winds observed at two meteorological stations – Michigan City, Indiana and St.

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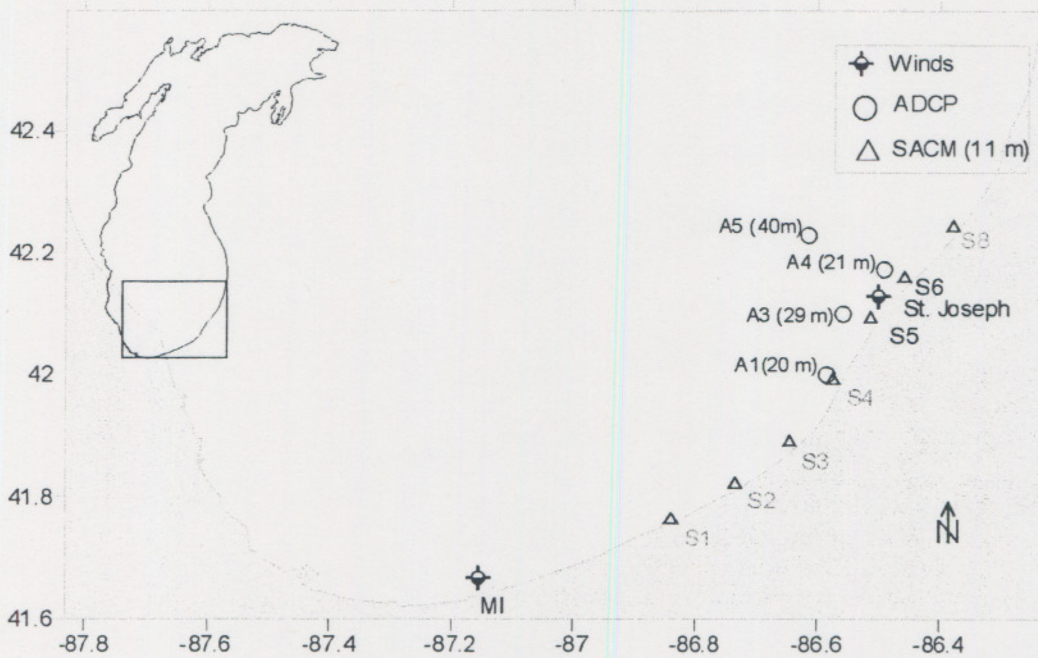

Fig. 1. Map of southern Lake Michigan showing instrumented moorings.

Joseph, Michigan (MI and St. Joseph, respectively, in Fig. 1) – are considered as a representative forcing. The wind stress was obtained from the quadratic law. The wind stress and current velocities were rotated to conform to the local shore and depth contours for calculating alongshore and cross-shore components. The alongshore and cross-shore components of wind stress and currents were subjected to a low-pass filter with a cutoff period of 18 to 24 h. Furthermore, the currents at two ADCP stations were averaged over the depth.

A time series of low-pass filtered currents show the flow reversals coupled with prevailing winds (Fig. 2). The alongshore currents exhibited oscillations corresponding to 2–5 days. The mean currents are towards the north at these locations. During a northerly (southward) storm from March 1 to March 10, 1999, the offshore flow increased considerably at nearshore stations; however, at station A5, located at a 40-m depth, no significant offshore flow is observed. The mean low-pass filtered currents show increased southwesterly (offshore) flow during the storm event compared to average winter conditions (Fig. 3a).

In order to estimate the horizontal exchanges in low frequency (>0.0416 cph) and high frequency (<0.0416 cph), the time series of low-pass filtered flow values $\bar{u}(t)$ and $\bar{v}(t)$ are subtracted from the observed hourly values to obtain $u'(t)$ and $v'(t)$. The root-mean-square values ($\sqrt{\bar{u}'^2}$ and $\sqrt{\bar{v}'^2}$) are used as a measure of the magnitude of velocity fluctuations. The kinetic energy of low-frequency motion (LFKE) and high-frequency motion (HFKE) are then simply given as {LFKE, HFKE} = $\{0.5(\bar{u}^2 + \bar{v}^2),\ 0.5(\bar{u}'^2 + \bar{v}'^2)\}$. The increase in the kinetic energy due to storm-forced winds at these frequency bands is calculated as the difference between the kinetic energy during storm events and the kinetic energy during the whole winter season (ΔLFKE and ΔHFKE). The rms values at station A4 over the depth (Fig. 3b) show that the fluctuations are non-isotropic and the magnitude of the cross-shore component is marginally higher than the alongshore component. During the March 1999 storm event, both alongshore and cross-shore fluctuations increased slightly in the upper layers. Figure 3c shows ΔLFKE and ΔHFKE for three ADCP stations (A1, A4 and A5). This figure

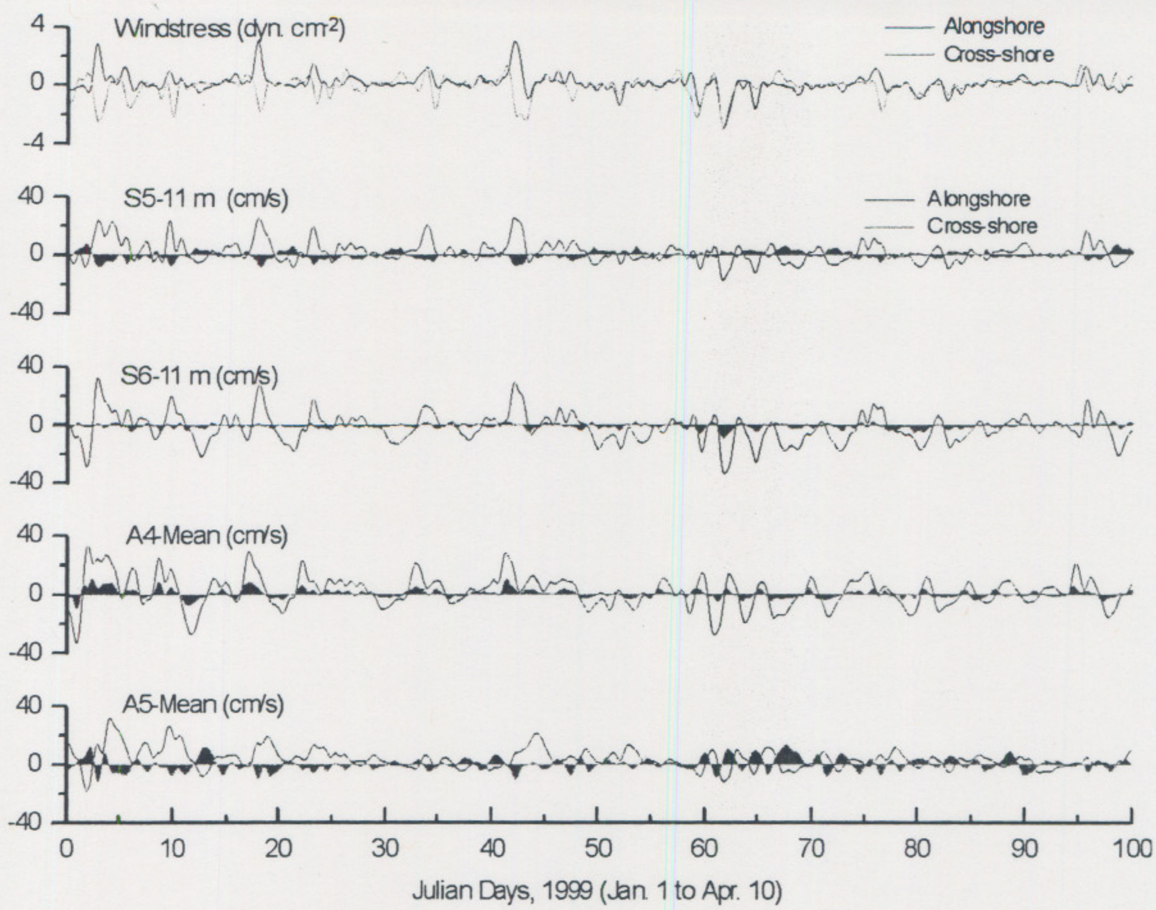

Fig. 2. Time series of alongshore and cross-shore low-pass filtered windstress (St. Joseph) and currents. The shaded area shows the period of the March 1999 storm event.

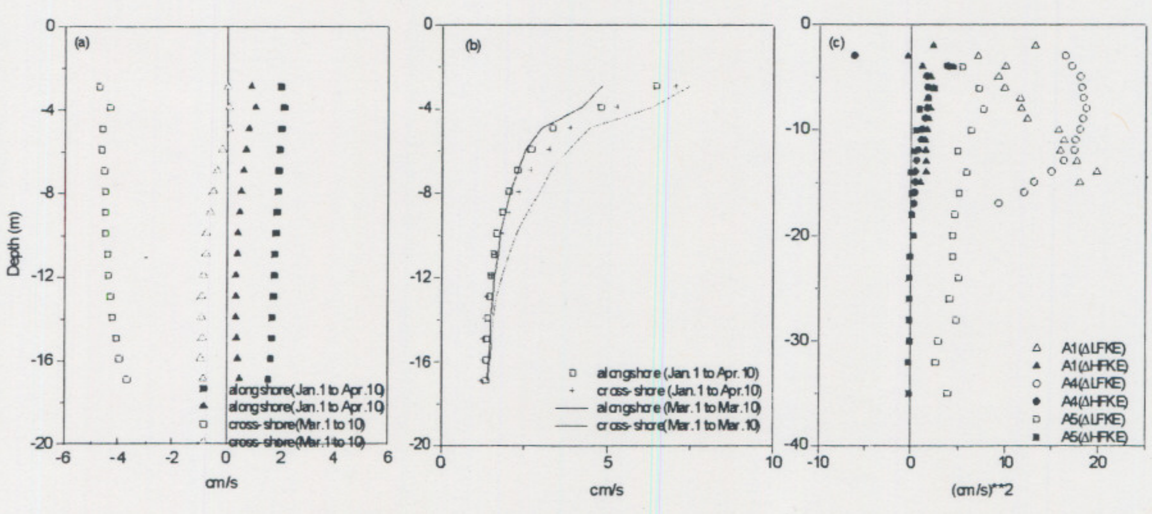

Fig. 3. (a) Means of low-pass filtered currents as a function of depth at station A4, (b) rms values of fluctuations at station A4, and (c) ΔLFKE and ΔHFKE at three ADCP stations.

clearly shows that the storm episode during March 1999 significantly increased the low-frequency currents, and comparatively small variation is observed in high-frequency fluctuations in the shallow waters. In the deeper waters, although low-frequency currents increased marginally, fluctuations have not shown significant variation. Although the time series of filtered currents at nearshore stations (S5 and S6) showed several occasions of offshore flow during the winter season, at intermediate depths (20–30 m), northerly storm events seem to be a major mechanism for offshore flow. The future analysis of these data will be directed toward the quantification of low-frequency motions such as vorticity waves that are responsible for cross-shore transport in southern Lake Michigan.

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